MONTHLY WEATHER REVIEW

CHARLES F. BROOKS, Editor.

VOL. 48, NO. 8.
W. B. NO. 717.

AUGUST, 1920.

CLOSED OCT. 4, 1920
ISSUED OCT. 28, 1920

MATHEMATICAL INQUIRY INTO THE EFFECT OF WEATHER ON CORN YIELD IN THE EIGHT CORN BELT STATES.

By H. A. WALLACE, Associate Editor of *Wallace's Farmer*.

INTRODUCTORY NOTE.

Within the past few years a number of mathematical studies have been published regarding the effect of weather on crops. Prof. J. Warren Smith, Mr. T. A. Blair, Mr. J. B. Kincer, Mr. J. Cecil Alter, Prof. H. L. Moore, and others have drawn attention to the great importance of utilizing statistical methods for the formulation of relations between the occurrence of certain agricultural, meteorological, or other phenomena, with alleged controlling factors. These are evidences of the advancement of the science of meteorology from the purely empirical stage to a more scientific one in which mathematical methods are employed to state relations rather than indefinite words and language.

The criticism is sometimes made that results of the statistical analysis are necessarily crude and inexact, and that large deviations from the theory are met with. This may be true, but it is capable of improvement will come with more advanced studies.

It is also alleged that capable students are able to do quite as well without the aid of the mathematical formulæ. This may be true, but the statistical data to prove it so have by no means been advanced; in fact, they are perhaps not available. Moreover, it must be recognized that the mathematical relations based on statistics are dependable and reliable. We know with a certain definiteness the range of scatter and deviation of the results. We know that very great deviations will occur but rarely. The claim that the forecaster can do as well without as with the aid of the formulæ is not sufficient. He must be able to surpass the formulæ, or his forecasting instinct is in the long run no better than the statistical equation. In other words, an examination of the current weather maps or the data bearing on a particular anticipated condition should enable the forecaster to conclude when the formula is going to fail, and shape his forecasts to accomplish a higher verification. If he is unable to do this his forecasting instinct is really of little avail, because the statistical methods will accomplish the same results without even considering the weather map or the current conditions. It would be interesting to conduct a comparative study to ascertain how much better a capable forecaster could do than the results arrived at by the statistical analysis.—*C. F. Marvin.*

INTRODUCTION.

As a result of the excellent pioneer work of J. Warren Smith, of the United States Weather Bureau, it is commonly believed that July rainfall is the all-important factor in determining the yield of corn in the central part of the corn belt. In the February, 1914, issue of the MONTHLY WEATHER REVIEW [1] J. Warren Smith examines in some detail by means of the correlation coefficient method the relationship between various weather factors and corn yield in the various corn-belt States and among other conclusions arrives at the following: "If the rainfall for calendar months be considered, that for July has a far greater effect upon the corn yield than rainfall for any other month."

Prof. Smith's conclusion as to the importance of rainfall in July in determining corn yields, while it is absolutely sound as far as Ohio and several other corn-belt States is concerned, does not apply to Iowa. The object of this paper is to examine, in somewhat greater detail than Prof. Smith has done in his published work, the relation between corn yield, rainfall, and temperature in the months of May, June, July, and August in each of the eight corn-belt States. For the most part the method of investigation will be by means of correlation coefficients, multiple coefficients of correlation, and lines of regression. The period studied in each State is a 29-year period from 1891 to 1919, inclusive.

Secular trend.—The secular or long-time trend of the corn yield for each State is determined after the customary manner such as is described on page 12 of the January, 1919, issue of the *Review of Economic Statistics*, published by Harvard University. The actual yields for each of the eight States for the 29-year period under consideration are taken from Department Bulletin 515 of United States Department of Agriculture and from the Yearbooks of the Department of Agriculture for 1916, 1917, 1918, and 1919. The method of secular trend when applied to the corn yields of Iowa for the 29-year period under consideration gives a value of 29.9 bushels for the year 1891, with an average yearly increase of 0.25 of a bushel, or 30.15 bushels for 1892, and so on by 0.25 bushel additions to 36.9 bushels for 1919. In like manner the normal corn yield in Ohio in 1919 based on the method of secular trend would be 40.5 bushels as compared with 30.7 bushels in 1891, the yearly addition since 1891 being 0.353 of a bushel. In Indiana the yearly addition is 0.233 bushel, the 1891 value is 31.1 bushels, and the 1919 value 37.6 bushels. In Illinois the average yearly increase is 0.12 bushel, the 1891 value is 32 bushels, and the 1919 value, 35.4 bushels. In Missouri* the average yearly increase is 0.044 bushels, the 1891 value is 26.9 bushels, and the 1919 value 28.1 bushels. In Nebraska* the secular trend is downward at the rate of 0.05 bushel annually, the value in 1891 being 26.2 and the value in 1919 being 24.8 bushels. In Kansas* the secular trend is also downward at the rate of 0.196 bushel annually from 22.7 bushels in 1891 to 17.2 bushels in 1919. In Minnesota the secular trend is upward at the rate of 0.342 bushel annually from 25.9 bushels in 1891 to 35.4 bushels in 1919.

Departures.—The next step is to determine the percentages which the actual yield is year by year above or below the normal yield as thus determined by the method of secular trend. For example, the normal yield in Iowa in 1919 was 36.9 bushels, according to the method of secular trend, whereas the actual yield was 41.6 bushels, or 13 per cent above. For each year of the 29-year period and for each of the eight States is determined in this way the percentage deviation of the actual yield from the normal yield as determined by the method of secular trend.

TEMPERATURES AND RAINFALL OF SUMMER MONTHS.

Averages.—Having determined the percentage deviations of the yields year by year above and below the normal as determined by the method of secular trend,

[1] 42: 78-93.

* In Kansas, Nebraska and Missouri the method of secular trend as applied to the 1891–1919 period may involve some error inasmuch as the weather seems to have been less favorable during the period 1911–1919 than during that of 1891–1899. In Kansas and Nebraska minor causes of the downward trend have been decrease in soil fertility and westward extension of the corn-growing area.

we next endeavor to determine to what extent these deviations are caused by deviations in the rainfall or temperature above or below the mean for the 29-year period. The average temperatures for the 29-year period for the eight corn-belt States for the months of May, June, July, and August are as follows:

TABLE 1.—*Average temperature (1891–1919).*

	May.	June.	July.	August.
	°F.	°F.	°F.	°F.
Iowa	59.8	69.2	74.0	72.0
Illinois	62.5	71.6	75.8	74.2
Indiana	62.4	71.3	75.3	73.6
Kansas	63.7	73.4	78.1	77.5
Minnesota	54.8	64.7	69.5	67.1
Missouri	64.9	73.4	77.3	76.3
Nebraska	58.9	68.9	74.3	72.8
Ohio	60.6	69.3	73.7	71.8

The average precipitation for the eight States for the months of May, June, July, and August is as follows:

TABLE 2.—*Average precipitation (1891–1919).*

	May.	June.	July.	August.
	Inches.	*Inches.*	*Inches.*	*Inches.*
Iowa	4.66	4.40	3.85	3.40
Illinois	4.22	3.84	3.49	3.32
Indiana	4.10	3.87	3.48	3.29
Kansas	4.67	4.63	3.73	3.32
Minnesota	3.51	4.17	3.63	3.40
Missouri	4.99	4.78	4.08	4.08
Nebraska	3.48	3.81	3.24	2.83
Ohio	3.73	3.79	3.94	3.27

Departures.—The next step is to determine the number of inches the precipitation is above or below the average year by year, as well as the number of the degrees the temperature is above or below the average year by year. For instance, in May, 1891, the Indiana actual rainfall was 1.6 inches, or 2.5 inches below the average of the 29-year period, which is 4.1 inches.

CORRELATION OF CORN YIELD WITH WEATHER.

After the deviations above or below the average in inches of precipitation or degrees of temperature have been secured for the months of May, June, July, and August for each of the eight States, the next thing to do is to find the correlation between the deviation of the yield from the normal as determined by secular trend and the deviation in the temperature or rainfall, as the case may be, for any given month.

May rainfall and corn yield in Kansas.—For example, determine the correlation between the yield of Kansas corn and the Kansas May rainfall. In 1891 the Kansas corn yield was 18 per cent above normal, and the Kansas May rainfall was 0.5 inch above the mean for the 29-year period. Likewise, in 1892 the Kansas corn yield was 9 per cent above normal, and the rainfall was 3 inches above the mean. The following table sets forth the values of the corn yield percentage deviations and the May rainfall deviation, the column of corn-yield deviations being called column A and the column of May rainfall deviations being called column B.

TABLE 3.—*Correlation of corn yield with May rainfall in Kansas.*

	A.	B.	AB.	
			Plus.	Minus.
1891	+18	+0.5	+ 9.0	
1892	+ 9	+3.0	+ 27.0	
1893	− 4	−0.8	+ 3.2	
1894	−49	−2.2	+ 107.8	
1895	+11	−2.3		−25.3
1896	+29	+1.2	+ 34.8	
1897	−16	−2.4	+ 38.4	
1898	−25	+1.9		−47.5
1899	+28	−0.4		−11.2
1900	− 9	−0.6	+ 5.4	
1901	−62	−2.9	+ 179.8	
1902	+46	+2.7	+ 124.2	
1903	+26	+5.3	+ 137.8	
1904	+ 4	+1.8	+ 7.2	
1905	+39	+0.2	+ 7.8	
1906	+47	−1.8		−84.6
1907	+13	−1.9		−24.7
1908	+13	+1.9	+ 24.7	
1909	+ 4	−0.3		− 1.2
1910	0	+1.4		
1911	−23	−1.9	+ 43.7	
1912	+24	−1.0		−24.0
1913	−83	−1.0	+ 83.0	
1914	+ 2	−1.5		−3.0
1915	+73	+3.0	+ 219.0	
1916	−60	−0.2	+ 12.0	
1917	−26	−0.5	+ 13.0	
1918	−42	0		
1919	−10	−1.1	+ 11.0	
Total			+1,088.8	−221.5

Summation AB = +867.3.

According to the method of correlation coefficients as used by Pearson and Yule the standard deviation of column A is 33.3, which, in effect, means that in Kansas the chances are about two out of three that the yield will not be more than 33.3 per cent above or below the normal. The standard deviation of column B is 1.94 inches, which means, in effect, that there are about two chances in three that the rainfall in May will not be more than 1.94 inches above or below the 4.7 mean. The summation of the product of column A by column B is 867.3. 867.3 divided by 29, which is the number of cases or years involved, is 29.9. 29.9 divided by the standard deviation of column A multiplied by the standard deviation of column B, or 64.6, gives +0.463. +0.463 is the correlation between Kansas corn yield and the Kansas May rainfall, perfect positive correlation being +1 and perfect negative correlation being −1.

Weather elements by months and corn yield in eight States.—By means of the method just illustrated correlation coefficients have been worked out in each of the eight States between yield, rainfall, and temperature in each of the four months, giving 64 correlation coefficients between yield and weather as in the following table:

TABLE 4.—*Correlation coefficients between corn, yield, and weather.*

	Yield and temperature.				Yield and rainfall.			
	May.	June.	July.	Aug.	May.	June.	July.	Aug.
Indiana	+0.200	−0.115	−0.474	+0.040	+0.072	+0.083	+0.591	+0.423
Illinois	+ .222	− .322	− .637	− .144	+ .096	+ .110	+ .651	+ .330
Iowa	+ .153	− .100	− .294	− .020	− .056	+ .117	+ .122	+ .273
Kansas	− .060	− .477	− .748	− .555	+ .463	+ .410	+ .770	+ .540
Minnesota	+ .224	+ .380	− .077	+ .400	+ .041	.000	+ .131	+ .422
Missouri	− .027	− .567	− .654	− .541	+ .263	+ .337	+ .534	+ .495
Nebraska	− .110	− .217	− .594	− .424	+ .432	+ .276	+ .587	+ .382
Ohio	+ .325	− .098	− .172	− .086	− .308	+ .142	+ .653	+ .350
Floyd County, Iowa	+ .320	+ .229	− .096	+ .170	+ .101	+ .083	− .085	+ .188
Polk County, Iowa	+ .085	− .382	− .510	− .240			+ .180	+ .492

Table 4 is worth very careful study. In the first place, I wish to call attention to the fact that so far as correlation between corn yield and rainfall in Ohio is concerned the results are practically identical with those of J. Warren Smith. His correlation between yield and June rainfall is +0.12 whereas mine is +0.132. For July rainfall he gets a correlation coefficient of +0.59 whereas mine is +0.653. For August he gets +0.37 whereas mine is +0.35.

So far as Ohio is concerned, July rainfall is unquestionably the dominating weather factor. The temperature in May, however, is also important, the correlation coefficient between May temperature and yield in Ohio being +0.325, which is almost as high as the correlation coefficient between August rainfall and yield.

In some States west of Ohio the temperature during July assumes an even more dominating part than the July rainfall. Note that in Illinois there is a correlation between July temperature and yield of −0.637, whereas between July rainfall and yield the correlation coefficient is +0.651. In Missouri there is a negative relation between July temperature and yield of −0.651, whereas between July rainfall and yield the correlation is only +0.534. July temperature seems to be even more important in Missouri than July rainfall. In Iowa and Minnesota it will be noted that July rainfall means practically nothing, the correlation coefficient being only +0.122 for Iowa and +0.131 for Minnesota. There is no very strong correlation coefficient for anything in Iowa, but the strongest is the negative relationship between July temperature and yield, of −0.294.

In each of the eight States I shall pick out factors which are more or less dominating so far as yield is concerned. For instance, in Indiana I shall take July temperature with a correlation coefficient of −0.474, July rainfall with a correlation coefficient of +0.591, and August rainfall with a correlation coefficient of +0.423. In the case of Illinois we shall take July temperature, July rainfall, and May temperature. It first glance it might be thought that August rainfall should be used instead of May temperature in view of the fact that the correlation coefficient between May temperature and rainfall is only +0.222. As a matter of fact, however, the correlation coefficient between August rainfall and corn yield in Illinois is more apparent than real, inasmuch as there is a tendency for dry Augusts to come in the same years as dry Julys, whereas there is only a very slight tendency for a hot May to be followed by heavy rainfall in July.

YIELD CORRELATED WITH COMBINATION OF THREE MOST IMPORTANT WEATHER FACTORS.

The next step is to find out the multiple coefficient of correlation between the yield on the one hand and the three selected factors on the other. This is done according to the following formula:

$$R^2=\frac{M}{1-r_{1,2}{}^2-r_{1,3}{}^2-r_{2,3}{}^2+2r_{1,2}r_{1,3}r_{2,3}}, \qquad \text{.....(1)}$$

where

$$M=\left\{\begin{matrix}(r_{0,1}{}^2+r_{0,2}{}^2+r_{0,3}{}^2-r_{0,1}{}^2r_{2,3}{}^2-r_{0,2}{}^2r_{1,3}{}^2-r_{0,3}{}^2r_{1,2}{}^2)\\ -2(r_{0,1}r_{0,2}r_{1,2}+r_{0,1}r_{0,3}r_{1,3}+r_{0,2}r_{0,3}r_{2,3})\\ +2(r_{0,1}r_{0,2}r_{1,3}r_{2,3}+r_{0,1}r_{0,3}r_{1,2}r_{2,3}+r_{0,2}r_{0,3}r_{1,2}r_{1,3})\end{matrix}\right\}$$

To apply this formula, suppose we take Missouri, for example, allowing 0 to represent the percentage deviation of the yield; 1 to represent deviation of June temperature in degrees above and below the mean; 2 to represent the deviation of July temperature; and 3 to represent deviation of August temperatures. $r_{0,1}$ represents the correlation coefficient between yield and June temperature; $r_{0,2}$ the correlation coefficient between yield and July temperature; $r_{0,3}$ between yield and August temperature; $r_{1,2}$ between June temperature and July temperature; $r_{1,3}$ between June temperature and August temperature; $r_{2,3}$ between July temperature and August temperature. Solving the equation and securing the multiple coefficient of correlation between yield in Missouri and the deviations of the June, July, and August temperature we secure as the multiple coefficient of correlation, 0.79.

TABLE 5.—*Multiple correlation coefficients between deviations of weather factors and corn yield.*

State.	Weather combination.	Correlation coefficient.
Missouri	June temperature, July temperature, August temperature.	0.79
Iowa	May temperature, July temperature, August rain.	.464
Iowa, Polk County	June temperature, July temperature, August rain.	.62
Iowa, Floyd County	May temperature, June temperature, August rain.	.405
Nebraska	May rain, July temperature, July rain	.67
Indiana	July temperature, July rain, August rain	.66
Minnesota	June temperature, August temperature, August rain.	.56
Ohio	May temperature, July rain, August rain	.746
Illinois	May temperature, July temperature, July rain	.81
Kansas	June rain, July rain, August rain	.862

LINES OF REGRESSION.

In the case of every State, with the possible exception of Iowa and Minnesota, these multiple coefficients of correlation are high enough to indicate that it is worth while going ahead and working out lines of regression, which we shall therefore undertake to do as the next step. The formula for working out the line of regression in a case of this sort where there are three factors determining a fourth factor is as follows:

$$x_0=a_1x_1+a_2x_2+a_3x_3 \qquad \text{.....(2)}$$

where

$$a_1=\frac{r_{0,1}(1-r_{2,3}{}^2)+r_{0,2}(r_{1,3}r_{2,3}-r_{1,2})+r_{0,3}(r_{1,2}r_{2,3}-r_{1,3})\sigma_0}{(1-r_{2,3}{}^2)+r_{1,2}(r_{1,3}r_{2,3}-r_{1,2})+r_{1,3}(r_{1,2}r_{2,3}-r_{1,3})\sigma_1}$$

$$a_2=\frac{r_{0,2}(1-r_{1,3}{}^2)+r_{0,3}(r_{1,2}r_{1,3}-r_{2,3})+r_{0,1}(r_{1,3}r_{2,3}-r_{1,2})\sigma_0}{(1-r_{1,3}{}^2)+r_{2,3}(r_{1,2}r_{1,3}-r_{2,3})+r_{1,2}(r_{1,3}r_{2,3}-r_{1,2})\sigma_2}$$

$$a_3=\frac{r_{0,3}(1-r_{1,2}{}^2)+r_{0,2}(r_{1,2}r_{1,3}-r_{2,3})+r_{0,1}(r_{1,2}r_{2,3}-r_{1,3})\sigma_0}{(1-r_{1,2}{}^2)+r_{2,3}(r_{1,2}r_{1,3}-r_{2,3})+r_{1,3}(r_{1,2}r_{2,3}-r_{1,3})\sigma_3}$$

Missouri corn yield.—Solving this formula, we find as an answer in the case of Missouri:

The percentage deviation in the yield of corn equals −2.8 of the departure of the June temperature from the average, in degrees, −4 of the departure of the July temperature from the average, in degrees, −1.5 of the departure of the August temperature from the average, in degrees.

The average June temperature for Missouri is 73.4° F., the average July temperature, 77.3° F., and the averaeg August temperature, 76.3° F. At the present time the normal corn yield in Missouri according to the method of secular trend is 28.1 bushels. Translating our last equation, we find that it means that at the present time for each degree June temperature is above 73.4° F. in Missouri the chances are that the Missouri corn yield will be cut by 0.8 bushels, whereas, for each degree that the June temperature in Missouri is below 73.4° F. the corn yield will be increased by 0.8 bushels. In the case of

July, for each degree that the Missouri temperature is above 77.3° F. the corn yield will be cut by 1.1 bushels, whereas for each degree that it is below 77.3° F. it will be increased by 1.1 bushels. In like manner, for each degree that the August temperature is above 76.3° F. the Missouri corn yield will be cut by 0.4 bushels, whereas for each degree that the Missouri August temperature is below 76.3° F. the yield will be increased by 0.4 bushels. Taking a specific case, when in Missouri the June temperature is 72.4° F., the July temperature, 75.3° F., and the August temperature, 75.3° F., we should expect a yield 0.8 bushels above normal because of the low June temperature, 2.2 bushels above normal because of the low July temperature, and 0.4 bushel above normal because of the August temperature, or a total of 3.4 bushels above normal, or a yield of 31.5 bushels per acre.

Predicted from formula, the yield of Missouri corn in 1891 should have been 23 per cent above the normal, whereas actually it was only 11 per cent; in 1892 it should have been 6 per cent above normal, whereas actually it was 2 per cent; in 1895 predicted from formula it should have been 14 per cent above normal, whereas actually it was 33 per cent; in 1901 it should have been 48 per cent below normal, whereas actually it was 63 per cent below normal. In spite of the rather high multiple coefficient of correlation of 0.79, our prediction formula is still somewhat inaccurate. Perhaps other weather factors than June, July, and August temperature should be taken into consideration. One of these is May temperature; and it is found that there is a correlation coefficient between May temperature and the discrepancies between the predicted yield and the actual yield of 0.22. Again making a new predicted yield on the basis of May temperatures being accounted for, we still find considerable discrepancy, and on examining the matter further we find that July and August rainfall combined correlates with these discrepancies to the extent of 0.41 (provided that the year 1915 is left out).

While as a general rule the corn yield in Missouri increases with low temperatures in June, July, and August, yet there is a possibility of too low temperatures even in Missouri. Also, there is a possibility of danger by too heavy sudden rains even in Missouri, although, as a general rule, the heavier the rain during the summer, the larger the corn yield. In 1915 the temperature and rainfall was such that according to the strict mathematical formula we should have expected a yield fully 27 per cent above normal. As a matter of fact, however, the weather in 1915 went to the extreme of being too cold and too wet even for Missouri conditions, and the yield was only 6 per cent above normal.[2] 1904 is an example of somewhat similar conditions, the season being too cold and wet for Missouri. In extremely cold, wet seasons in Missouri the result normally is a crop which is about average, instead of a crop 25 per cent to 30 per cent above normal, as would be expected from a strict interpretation of the mathematical formula. It is necessary that there should be an average temperature deficiency below the average of at least 2½° for each of the months of June, July, and August in order to prevent Missouri corn from being benefited by coolness and wetness.

[2] Flooded bottoms cut the yield.—C. F. B.

PREDICTING FORMULÆ FOR CORN YIELDS.

The following predicting formulæ have been worked out for each of the States by means of formula (2).

Iowa:

$$x_0=0.77x_1-1.4x_2+1.26x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of May temperature from average in degrees.
x_2=deviation of July temperature from average in degrees.
x_3=deviation of August rain from average in inches.

Illinois:

$$x_0=0.98x_1-4.33x_2+4.38x_3$$

where x_0=per cent deviation in yield.
x_1=deviation of May temperature from average in degrees.
x_2=deviation of July temperature from average in degrees.
x_3=deviation of July rain from average in inches.

Ohio:

$$x_0=0.8x_1+1.9x_2+0.9x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of May temperature from average in degrees.
x_2=deviation of July rain from average in inches.
x_3=deviation of August rain from average in inches.

Kansas:

$$x_0=3.7x_1+10.7x_2+7.5x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of June rain from average in inches.
x_2=deviation of July rain from average in inches.
x_3=deviation of August rain from average in inches.

Minnesota:

$$x_0=1.6x_1+0.8x_2+4.2x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of June temperature from average in degrees.
x_2=deviation of August temperature from average in degrees.
x_3=deviation of August rain from average in inches.

In applying the Minnesota formula to the Minnesota averages it is well to remember that the average temperature for Minnesota as a whole is about 2° below the average of the corn-growing part of Minnesota. For corn-growing Minnesota the St. Paul temperature figures are probably better than those for the State as a whole. The St. Paul averages are 58° for May, 67° for June, 72° for July, and 69° for August.

Floyd County, Iowa:

$$x_0=1.65x_1+1.14x_2+1.83x_3$$

where x_0=deviation in per cent of yield.
x_1=deviation of May temperature from average in degrees.
x_2=deviation of June temperature from average in degrees.
x_3=deviation of August rain from average in inches.

Polk County, Iowa:

$$x_0=-0.8x_1-2.4x_2+3.4x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of June temperature from average in degrees.
x_2=deviation of July temperature from average in degrees.
x_3=deviation of August rain from average in inches.

Indiana:

$$x_0=-1.6x_1+3.6x_2+1.5x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of July temperature from average in degrees.
x_2=deviation of July rain from average in inches.
x_3=deviation of August rain from average in inches.

Nebraska:

$$x_0=3.48x_1-2.96x_2+3.08x_3$$

where x_0=per cent deviation of yield.
x_1=deviation of May rain from average in inches.
x_2=deviation of July temperature from average in degrees.
x_3=deviation of July rain from average in inches.

IOWA WEATHER AND YIELD OF CORN.

In Iowa the multiple coefficient of correlation between yield and May temperature, July temperature, and August rain is disappointingly low, being only 0.464.

Since Iowa is probably the most important of all the corn States, it is felt to be decidedly worth while to work out the Iowa weather-corn yield problem in considerable detail. Superficial examination of the evidence leads to the conclusion that the low correlation coefficient in Iowa is due to the fact that in Iowa there are some seasons and some sections when the yield is short because of the too cool weather during the greater part of the summer, whereas in other years the yield is too short because of too hot weather. Also it is a matter of observation that in exceedingly hot seasons the yield is oftentimes excellent in northern Iowa, whereas in southern Iowa the yield will be very seriously damaged, and vice versa in cool seasons. Obviously, therefore, the method of correlation coefficients is not very well adapted to examining the effect of weather on corn yield in Iowa.

TEMPERATURE AND RAINFALL AS AFFECTING THE YIELD OF CORN IN POLK COUNTY, IOWA.

In order to get a little closer to the problem let us work with Polk County, Iowa, for the 29-year period, 1891 to 1919, inclusive. The yields in this case are taken from the Iowa State Crop Reporting Service and the secular trend is secured for these yields and the percentage deviations above and below the normal is secured in just the same way as for the eight corn-belt States. Temperatures and rainfall are taken from the reports of the Des Moines weather bureau as compiled and published by Chas. D. Reed, of the Des Moines weather bureau, in a little pamphlet early in 1920. Using the method of correlation coefficients we find that the relationship between May temperature and corn yield in Polk County, Iowa, is +0.085, between June temperature and corn yield −0.382, between July temperature and corn yield −0.510, between August temperature and corn yield −0.240, between July rainfall and corn yield 0.180, and between August rainfall and corn yield 0.492. The three most important factors apparently are June temperature, July temperature, and August rainfall. The multiple coefficient of correlation between these three factors and the yield is 0.62, which is somewhat higher than the multiple coefficient of correlation secured for the entire State between the three leading factors and the yield. Applying now common sense to the data and realizing that certain years can be too cold for corn in Polk County and others too hot, and that especially May, June, and August can be too cold, we arrive roughly by the cut-and-try method, backed up, also, by our preliminary examination by means of correlation coefficients, at the following tables:

TABLE 6a.—*Corn yield in Polk County, Iowa, as affected by May temperature.*

Temperature.	Corn yield.	Temperature.	Corn yield.
55° F.	15 per cent cut from the normal as secured by method of secular trend.	61° F.	1 per cent above normal.
		62°	2 per cent increase above normal.
56°	5 per cent cut from normal.	63°	3 per cent increase above normal.
57°	3 per cent cut from normal.		
58°	2 per cent cut from normal.	64° or higher.	4 per cent increase above normal.
59°	1 per cent cut from normal.		
60°	No cut from normal.		

TABLE 6b.—*Corn yield in Polk County, Iowa, as affected by June temperature.*

Temperature.	Corn yield.	Temperature.	Corn yield.
65° F.	5 per cent cut from normal as secured by method of secular trend.	71° F.	1 per cent above normal.
		72°	No increase above normal.
66°	2 per cent cut from normal.	73°	1 per cent cut from normal.
67°	1 per cent cut from normal.	74°	2 per cent cut from normal.
68°	No cut from normal.	75°	3 per cent cut from normal.
69°	1 per cent increase above normal.	76°	4 per cent cut from normal.
70°	2 per cent increase above normal.	77°	5 per cent cut from normal.

It will be noted that in the case of June temperature it is assumed that both exceedingly low and exceedingly high temperatures are harmful to corn, and that there is a range of from about 68° to 72° that is neutral or slightly beneficial. It might very possibly be true that a temperature of 77° in June would not cut the yield by as much as 5 per cent provided there was plenty of rain. However, so far as Polk County is concerned we have no means of knowing whether or not this would be the case, inasmuch as the only year when the temperature was anywhere near this high was in 1911, when the temperature was 77.5° and when the rainfall was 0.75 inch. It might very well be, therefore, that the higher temperatures in June would not prove harmful provided there were more than 3 inches of rainfall. In fact, it is believed that with 3 inches or more of rainfall temperatures up to 75°, at least, might prove to be distinctly beneficial. So far as Polk County is concerned, however, it seems scarcely worth while to construct a chart taking into consideration both rainfall and temperature in June, inasmuch as only once during the past 29 years has the temperature been so very high and the rainfall moderately heavy. In June, 1914, the temperature was 74.4° and the rainfall was 3.9 inches. This combination of moderately high June temperature with good rain proved to be decidedly favorable, but it is the only year of its kind on which to base a judgment

TABLE 6c.—*Corn yield in Polk County, Iowa, affected by August temperature.*

Temperature.	Corn yield.	Temperature.	Corn yield.
67° F.	10 per cent cut below normal corn yield as secured by method of secular trend.	73° F.	3 per cent increase above normal.
		74°	2 per cent increase above normal.
68°	6 per cent cut below normal.	75°	1 per cent increase above normal.
69°	3 per cent cut below normal.	76°	3 per cent cut below normal.
70°	1 per cent cut below normal.	77°	6 per cent cut below normal.
71°	1 per cent increase above normal.	78°	12 per cent cut below normal.
72°	3 per cent increase above normal.	79°	20 per cent cut below normal.

Moderately warm weather during August is essential to ripen up the corn in Polk County, especially if the season earlier has been at all backward. However, if the temperature during August averages 76° the chances are that there has been some exceedingly hot weather during the first 10 or 12 days of August, and that this hot weather has come just at the time when hot weather and drought are likely to do the corn the most damage, just when the kernels are first being formed. It is

believed, therefore, that the very sudden increase in the size of the cuts in the lower part of the August temperature table is well founded.

So far as the month of July is concerned, it will be remembered that there is a (negative) correlation of −0.51 between July temperature and the corn yield in Polk County, indicating that ordinarily the cooler the July the greater the corn yield. When the temperature averages below 71° in July, however, it is very doubtful if the corn plant is benefited by any further decrease in temperature, especially if the rainfall is heavy and there is rather less than the normal amount of sunshine. Reasoning from the data presented by Prof. T. A. Kiesselbach in Research Bulletin No. 6 of the University of Nebraska, we know that corn plants transpire moisture much less rapidly when the temperature is 70° than when the temperature is 80°. Prof. Kiesselbach's data would indicate, in fact, that a normal acre of corn plants during 30 days of the middle of the summer will transpire at the rate of about 3½ inches of rainfall when the mean temperature is around 70°, as compared with over 6 inches of rainfall when the temperature is over 80°. Not only will the corn plants themselves transpire far more moisture through their leaves when the temperature is 80° than when the temperature is 70°, but there will also be a tendency for a greater evaporation of moisture from the soil itself. It is believed that the chief effect of high temperatures in July on the corn plant in Polk County is rather indirect, through causing increased transpiration of water through the leaves of the corn plant. On this assumption, therefore, the following table has been prepared which indicates the theoretical increases or cuts to be made in the corn yield from the normal base as secured by the method of secular trend.

TABLE 7.—*Relation between Polk County, Iowa, corn yield and different amounts of July rainfall and different degrees of July temperature.*

Inches rain.	0.25	0.50	0.75	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0 or more.
°F.														
68	.....	.....	.....	.....	.....	.....	+ 6	+ 5	+ 3	+ 2	+ 1	0	0	− 3
69	.....	.....	.....	.....	.....	.....	+13	+12	+10	+ 8	+ 6	+ 4	+ 2	0
70	.....	.....	.....	.....	.....	.....	+14	+14	+14	+14	+13	+ 9	+ 5	+ 3
71	.....	.....	.....	.....	.....	+12	+15	+18	+20	+18	+14	+12	+ 9	+ 5
72	.....	.....	.....	.....	.....	+10	+13	+16	+18	+20	+16	+13	+10	+ 6
73	.....	.....	.....	.....	.....	+ 9	+12	+15	+17	+20	+18	+14	+12	+ 7
74	.....	.....	.....	.....	+ 5	+ 8	+11	+14	+17	+20	+18	+15	+12	+ 8
75	.....	.....	.....	.....	+ 4	+ 7	+10	+13	+17	+20	+18	+16	+13	+ 9
76	−25	−15	− 3	0	+ 3	+ 6	+ 9	+12	+16	+19	+18	+17	+13	+10
77	−35	−22	−10	− 6	+ 1	+ 4	+ 7	.....	.....	.....	.....	.....	.....	.....
78	−45	−30	−15	− 9	− 2	+ 1	+ 4	.....	.....	.....	.....	.....	.....	.....
79	−55	−35	−20	−14	− 5	− 2	+ 1	.....	.....	.....	.....	.....	.....	.....
80	−65	−40	−25	−18	− 9	− 5	− 2	.....	.....	.....	.....	.....	.....	.....
81	−75	−45	−35	−24	−13	− 8	.....	.....	.....	.....	.....	.....	.....	.....
82	−85	−50	−45	−31	−18	−11	.....	.....	.....	.....	.....	.....	.....	.....
83	.....	−60	−50	−38	−24	−15	.....	.....	.....	.....	.....	.....	.....	.....
84	.....	−65	−55	−45	−30	−20	.....	.....	.....	.....	.....	.....	.....	.....

All practical farmers know that heavy May rainfall harms the corn crop in Polk County by delaying the preparation of the seed-bed and by delaying the date of planting. I therefore give the following table:

TABLE 8.—*Relation between corn yield and May rainfall in Polk County, Iowa.*

Rainfall.	Corn yield.	Rainfall.	Corn yield.
Inches.		*Inches.*	
11	10 per cent cut below normal as secured by method of secular trend.	9	6 per cent cut below normal.
		8	4 per cent cut below normal.
		7	3 per cent cut below normal.
10	8 per cent cut below normal.	6	1 per cent cut below normal.

With soil of the type prevailing over the greater part of Polk County there is a considerable reserve supply of moisture carried into the months of July and August from earlier in the season. Prof. Kiesselbach's experiments with measuring the transpiration from corn plants (op. cit.) indicate that there is a period of 20 or 30 days in late July and early August when corn is drawing on the soil for nearly twice as much water as normally falls at that time. The reserve supply of moisture carried over, therefore, from early in the season may occasionally become a determining factor. The following table is devised for the purpose of taking into account this proposition of a reserve supply of moisture, a proposition which becomes especially important in seasons when the months of May, June, and July are hot as well as dry.

If the 92-day period from May 1 to July 1 has averaged over 70° daily, and the July rainfall is less than 3 inches, the yield will vary from the normal according to the total rainfall in April, May, June, and July, in inches, as follows:

TABLE 9.—*Relation between corn yield and total rainfall in April, May, June, and July in Polk County, Iowa.*

Total rainfall.	Corn yield.	Total rainfall.	Corn yield.
Inches.		*Inches.*	
5	25 per cent cut from the normal as secured by the method of secular trend.	9	4 per cent cut.
		10	No cut.
		11	4 per cent increase.
6	20 per cent cut.	12	8 per cent increase.
7	14 per cent cut.	13	12 per cent increase.
8	8 per cent cut.	18	14 per cent increase.

It is believed that this matter of reserve rainfall is chiefly important only in years when the three months of May, June, and July have been unusually warm. The only years of this character in the past 29 years in Polk County have been 1894, 1901, 1911, 1913, 1914, 1918, and 1919. In 1894 the total rainfall during the months of April, May, June, and July was only 5 inches, and it is obvious that this very small amount of early-summer rainfall must have very much intensified the serious effects of the drought and heat in July and August. Again, in 1901 there was a total of only 8 inches of rainfall in the months of April, May, June, and July, and again the effects of late summer heat and drought were intensified. In 1918 and 1919, however, there were 14 and 18 inches of rainfall, respectively, in the four-months period from April to July, inclusive. This rainfall was enough to create somewhat of a reserve to withstand a very considerable degree of heat and drought during July and August of 1918 and 1919.

Still one more table is necessary, that dealing with the effect of August rainfall on Polk County corn yield:

TABLE 10.—*Effect of August rainfall on Polk County corn yield.*

Rainfall.	Corn yield.	Rainfall.	Corn yield.
Inches.		*Inches.*	
0.5	20 per cent cut below normal as secured by method of secular trend.	3	1 per cent increase above normal.
		3.5	2 per cent increase above normal.
1.5	15 per cent cut below normal.	4	3 per cent increase above normal.
2	7 per cent cut below normal.		
2.5	3 per cent cut below normal.	4.5	4 per cent increase above normal.
	No cut below normal.		

By using the foregoing tables (6–10) it is possible to predict the yield of corn in Polk County, Iowa, with considerable accuracy, the correlation between the predicted yield and the actual yield being 0.92.

The most marked discrepancy between the predicted yield as secured by the tables and the actual yield was in the year 1897, when the actual yield was 17 per cent below normal, and the predicted was 6 per cent above. In 1897 the damage, without much question, was caused by a cumulative drought. After a rainfall of 7 inches in April, the drought began, and there were only 2.3 inches of rain in May, 3.1 inches in June, 2.9 inches in July, 1.8 inches in August, and 1.6 inches in September. Ordinarily Polk County corn does very nicely with a rainfall of 2.9 inches in July and 1.8 inches in August, provided the temperatures are not too high. In this particular year (1897), however, it would seem that the very heavy rainfall in April must have delayed plowing or put the soil out of condition, or, possibly, that the rather short May and June rainfall allowed the slightly deficient July and August rainfall to have a greater effect than would otherwise have been the case.

Beginning north of Des Moines about 50 miles and extending to the Minnesota border is a wonderful corn-growing section, which, so far as the relation of climate to corn yield is concerned, is of an altogether different type from that section from Des Moines south. For instance, in Floyd County there are the following correlation coefficients between various weather factors and the corn yield, for the 1891–1919 period: May temperature +0.32, June temperature +0.22, July temperature −0.10, August temperature +0.17, July rainfall −0.09, August rainfall +0.19, May rainfall +0.101, and June rainfall +0.083. Warm Mays are apparently much more important in Floyd County than in Polk County. Junes and Augusts which are warmer than the average tend to help the corn yield in Floyd County whereas in Polk County those Junes and Augusts which are warmer than the average ordinarily harm the corn yield. When an attempt is made to draw up a schedule of tables for Floyd County as for Polk County, it is found that there are a number of difficulties in the way. There are too many years when the season apparently contradicts itself.

In a season which is of a distinct type throughout, such as 1915, which was cool and wet, it may work all right to say that the 1915 May temperature of 53° cut the yield by 10 per cent, that the 62° June temperature cut the yield 20 per cent, and the 64° August temperature cut the yield another 20 per cent, making a total cut of 50 per cent. When a given season is mixed in its tendencies, however, it is difficult to predict just what will happen in northern Iowa. For instance, in 1912 May and July were warm, whereas June and August were cool. The rainfall was practically normal throughout. Any system of tables which would apply to the bulk of the past 29 years in Floyd County would credit the year 1912 with a crop only slightly above normal, whereas it actually was estimated at 42 per cent above normal.

While the correlation coefficients for Floyd county do not reveal any tendencies for the corn yield to be seriously affected by heat and drought in July and August, there nevertheless were certain years when the yield was unquestionably very seriously cut by heat and drought during the latter part of the summer, notably in 1894 and 1901—an accumulative drought existing since spring causing the trouble in 1894 and high July heat causing the trouble in 1901.

Even in northern Iowa it should be possible after very careful study to devise some kind of system of estimating the corn yield from the weather with a fair degree of accuracy. However, it will never be possible to estimate the corn yield in northern Iowa by knowing the weather with as great a degree of accuracy as is possible in the rest of the corn belt. Too much rainfall very often causes damage in the northern part of Iowa, but it is impossible to tell merely by examining monthly rainfall records just when the rainfall was too heavy. The worst corn crop failure of the past 29 years in Floyd County was in 1915, a year when the four months of May, June, July, and August averaged 5° below normal and when the May rainfall was 3 inches above normal. In 1891, when the temperature for the four summer months was almost as low as in 1915, with an average of 4.5° below normal for the four summer months, the yield was 12 per cent above normal; but in 1892 the rainfall in May was only 1.9 inches, or nearly 2 inches below normal. It seems to be a double combination of cold and wet which does the most damage in Floyd County, and probably in northern Iowa generally. The year of heaviest May rainfall in Floyd County was in 1902, with 9.2 inches, but that year the May temperature was 5° above normal and the yield of corn was 12 per cent above normal. More or less superficial examination of the data, backed up by a study of correlation coefficients, would lead to the conclusion that cold during May, June, and August does considerably more damage than an excess of rain, but that cold will not do its maximum damage unless accompanied by heavy rain, especially in May. It is suggested that unduly heavy rains during July and early August may possibly damage the corn yield in northern Iowa in rather backward seasons by decreasing the amount of sunshine, the effect of the decreased amount of sunshine being felt only in years when the temperature throughout the summer is rather below normal.

CONCLUSIONS.

July rainfall, while a dominating factor in determining corn yield in Ohio, is not such a dominating factor in many of the other corn-belt States, and in northern Iowa especially July rainfall ordinarily has very little influence on corn yield. Each State is a specific problem in itself, and the probabilities are that each county in a State is a specific problem. In Polk County, Iowa, for instance, it was found that there is a tendency for warm Junes to harm the corn yield, each degree of increase in temperature cutting the corn yield by 0.8 of 1 per cent, whereas in Floyd County, Iowa, only 150 miles farther north, warm Junes benefit the corn yield, each degree increase in June temperature adding 1 per cent to the corn yield.

The problem of predicting corn yield from the weather is relatively simple in the southern half of the corn belt, notably in Kansas, Missouri, and southern Illinois where drought and heat in June, July, and August are the chief influences. The problem is to measure the degree of the drought and heat with accuracy.

Careful examination of the rainfall, temperature, and corn yield data in the various corn-belt States leads to the belief that while the method of correlation coefficients is very useful for preliminary examination of the data, and while this method gives fairly good predicting formulæ in the southern part of the corn belt, yet it is not at all well adapted to the northern part of the corn belt, and especially to notthern Iowa. The relationship between corn yield and July temperature, for instance, is not strictly linear, but more in the nature of a horse-shoe curve. For instance, when the July temperature is 68° the yield may possibly tend to be 6 per cent above

normal; when it is 69° the yield may tend to be 13 per cent above normal; when it is 70° the yield may tend to be 14 per cent above normal; when it is 71° the yield may tend to be 15 per cent above normal; when it is 72° the yield may tend to be 13 per cent above normal; when it is 73° the yield may tend to be 12 per cent above normal; when it is 74° the yield may tend to be 10 per cent above normal; when it is 75° the yield may tend to be 8 per cent above normal; when it is 76° the yield may tend to be 6 per cent above normal; when it is 77° the yield may tend to be 4 per cent above normal; when it is 78° the yield may tend to be 2 per cent above normal; when it is 79° the yield may tend to be 2 per cent below normal. (This is when the rainfall is constant.) July rainfall and corn yield also apparently tend to have a relationship of somewhat this type, a rain of more than 4½ inches in July ordinarily doing little if any more good than a rainfall of 4 inches. In fact, in some years exceedingly heavy July rains seem to have done harm in northern Iowa. Practically none of the weather factors has a strictly linear relationship to corn yield. In the case of May temperature, for instance, a temperature of less than 54° is apparently very severely damaging in the north central part of the corn belt, much more damaging than a straight line of regression would indicate. In years when the May temperature is 6° or 7° below normal it is probable that the yield is cut 20 per cent or 25 per cent below normal, whereas the method of a straight line of regression would indicate a cut of only about 7 per cent below normal. When the temperature is only 2° below normal, however, it is doubtful if the corn yield is really affected by as much as the 2 per cent which the line of regression would indicate. There is a need of developing special types of curves for expressing the different relationships more accurately than straight lines of regression express it. For practical purposes it is probably just as well first to get a general idea of the importance of the various factors at work by using the theory of multiple correlation, and then by applying common sense derived from observation of the methods of corn culture in various sections work out tables somewhat after the fashion of the tables worked out in predicting the yield of corn in Polk County, Iowa. These tables are rather roughly worked out and are certainly open to objection from the standpoint of refined mathematics, but they illustrate the principles involved.

DISCUSSION.

(1) In the central portions of the corn belt much of the corn is grown on bottom lands, subject to overflow. In years of late spring or early summer floods, this corn has to be replanted, and this delays it so much that it is likely to be frosted before reaching maturity. In consequence, the yield for the State is reduced. This disturbing factor, only indirectly connected with the weather of the particular State, could be eliminated by using figures of the yield per acre of corn harvested for grain.

(2) Owing to the differences in the dates of planting corn one year and another, the weather of a particular month does not affect corn in the same way year after year, even if the weather of that month should be identical in, say, two years under consideration. This difficulty could be eliminated by taking the weather not by calendar months but by periods following the mean date when corn was planted in the region each year.

(3) The use of periods as long as a month is unsatisfactory in that a certain month with a mean temperature about normal may appear to have had usual temperatures when in reality it was one with a very hot period and a very cool period, a combination not at all unlikely to occur. The week would seem to be the better unit to use.

(4) Considering (2) and (3) above in conjunction, Prof. Smith's studies of the effect of weather for the 10 days following the average date of tasseling, for example, if applied individually to each year instead of by use of averages, would probably give consistent results.

(5) In the northern part of the corn belt much of the corn is planted without any real hope of harvesting it for grain. In a good year, that is, in a year with weather that would be normal 100 or 200 miles farther south, the corn is harvested with as good a yield as is usually obtained a little farther south. In a poor year, when the weather delays the crop, or when a frost comes unusually early, the corn is harvested for silage. It is evident that the weather of May, June, July, and August may actually be ideal for corn, but yet an early frost may reduce the yield 20 per cent or lower over a large portion of the northern part of the corn belt. This would be like throwing a monkey-wrench into the wheels of the formula.

Thus, the length of the growing season each year and the speed of the development of the crop are important factors to be considered in computing the yield for the northern part of the corn belt.

To make a study in accordance with these suggestions would probably require an impossible amount of labor for one person. But if one investigator takes one aspect or one locality and others do likewise, there may be some hope of a mathematical solution of the effect of weather on crop yields along much more detailed lines than hitherto.—*Charles F. Brooks.*

DAMAGE TO CROPS BY WEATHER.

The Bureau of Crop Estimates publishes a table in the *Monthly Crop Reporter* each year showing the per cent of damage to crops in the United States due to different causes. The figures are from estimates by their large corps of crop correspondents, and "may be regarded as index numbers reflecting the relative influence yearly of different factors affecting yields."

The table below gives the average damage, by the different factors, for the period from 1909 to 1919, inclusive, except for apples and berries, which is from 1912 to 1919:

	Deficient moisture.	Excessive moisture.	Floods.	Frost or freeze.	Hail.	Hot winds.	Storms.	Total weather.	Plant disease.	Insect pests.	Animal pests.	Defective seed.	Total.
Wheat	12.4	2.0	0.3	4.5	1.1	2.0	0.3	22.9	2.7	2.1	0.2	0.2	28.8
Corn	16.3	4.0	.9	2.9	.4	2.2	.5	27.7	.2	2.7	.2	.7	32.1
Oats	13.4	2.7	.3	.8	.8	1.9	.4	20.8	1.7	.9	.1	.2	24.5
Barley	17.1	1.8	.1	.8	1.3	3.2	.4	24.9	1.7	.7	.3	.1	28.7
Flax	21.1	1.3	.1	4.0	1.7	3.0	.2	31.8	2.3	.9	.1	.3	36.4
Rice	6.7	3.1	1.5	.3	(1)	.4	1.8	14.1	1.2	.8	.3	.1	19.0
Potatoes	14.4	3.1	.2	1.6	.1	.7	.1	20.7	4.4	3.2	.1	.3	30.0
Tobacco	8.7	3.7	.6	1.1	.8	.2	.3	15.8	.4	2.6	.....	.1	20.5
Hay	13.4	1.7	.3	1.7	.1	.6	.2	18.4	.1	.5	.1	.1	20.4
Apples	5.4	1.6	.2	14.6	.8	.5	.9	24.9	3.7	3.6	.1	.....	39.6
Berries	9.3	1.7	.2	7.3	.5	.6	.2	20.3	1.1	.6	.1	.....	24.9
Cotton	12.3	4.3	1.0	1.4	.5	1.6	.7	22.3	2.0	9.7	(1)	.2	35.5

[1] Less than 0.05 per cent.

It will be noted that a very large part of the total damage or loss is due to unfavorable weather; also that deficient moisture is the greatest single damaging factor in connection with every crop, except apples. Low temperature causes nearly three times as much damage to apples as dry weather.—*J. Warren Smith.*